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Engineering**www.elsevier.com/locate/procedia**MRS Singapore - ICMAT Symposia Proceedings**7th International Conference on Materials for Advanced Technologies**Investigations on Dissimilar Weldments of Inconel 625 and AISI 304**

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*School of Mechanical & Building Sciences, VIT University, Vellore - 632014, India***Abstract**

This paper investigates the weldability, metallurgical and mechanical properties of the dissimilar joints of Inconel 625 and AISI 304. Dissimilar joints were obtained by gas tungsten arc welding process employing ERNiCrMo-3. Tensile fracture occurred at the parent metal of AISI 304 in all the trials. The structure-property relationships on these dissimilar weldments were evaluated using the combined techniques of optical microscopy and SEM /EDAX techniques.

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Keywords: Inconel 625; austenitic stainless steel, AISI 304; gas tungsten arc welding; SEM/EDAX analysis

1. Introduction

Dissimilar joints of Inconel 625 and austenitic stainless steel are widely used in the nuclear, petrochemical industries. As reported by Shah Hosseini et al. [1] Inconel is a relatively expensive alloy, a cheaper material with good properties can be used in lower risk conditions to reduce material costs. Austenitic stainless steel is a prevalent material used in high temperature applications. The typical applications of these bimetallic combinations include the sub-scale boiler employed for Advanced Stirling Conversion System project as reported by Robert Dreshfield [2]. The materials used to build this sub scale boiler were AISI 316 stainless steel for the condenser and Inconel 625 with a type 304L stainless steel wick for the boiler.

Lee and Fontana [3] explained that presence of delta ferrite in the autogenous welding of stainless steel can also improve solidification cracking of the weld metal. Fine dendritic structure of weld in this steel enhances the fracture toughness and ductility. Patterson et al. [4] also reported the use of autogeneous gas tungsten arc welds to join alloy 625 and 304L stainless steel. The author reported that the welds produced from the technique were found to be susceptible to weld solidification cracking

The critical issue in the joining of Ni based superalloy and austenitic stainless steel is the selection of appropriate filler wire. Naffakh et al. [5] employed Gas Tungsten Arc (GTA) welding for joining Inconel 657 and AISI 310 using nickel-based corresponding to Inconel 82, Inconel A, Inconel 617 and 310 austenitic stainless steels. Further the authors reported the failure occurred at the parent metal of Inconel 657 in all the weldments.

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Devendranath Ramkumar et al. [6] investigated the performance of GTA weldments of Monel 400 and AISI 304 using E309L and ERNiCu-7 filler wires and analyzed the hot corrosion behavior in the cyclic molten salt environment and air oxidation environments at 600 °C. It was reported by the authors that enrichment of Ni at the weld zone reduces the formation of carbon denuded soft zone. Jeng et al. [7] investigated the microstructure of the Alloy 690 and SUS 304L stainless steel weldments obtained by GTA welding techniques employing different filler metals. They observed the precipitation of Cr-carbides at the inter-dendritic regions due to the multi-pass welding. The Cr content near the grain boundary decreases as a result of Cr-carbide precipitates. It has been proposed that the Cr depletion caused by the Cr-carbide precipitation along the grain boundary results in a reduction in the corrosion resistance to inter-granular attack. A comparative analysis on the Continuous Current GTA (CCGTA) and Pulsed Current GTA (PCGTA) welding of Inconel 617 was done by Farahani et al. [8]. The authors reported that the dendrite spacing of weld metal in the constant current was wider than pulsed current welding. These dendritic structures are associated with greater degree of segregation and are more susceptible to cracking.

Hitherto, as evident from the open literatures, there is a need to assess the weldability, microstructure and mechanical properties of the Inconel 625 and AISI 304 bimetallic joints. Since these bimetallic combinations have accrued potential benefits in the industrial sectors, the throughput of this research work assumes to have significance. In this research article, the dissimilar metals of Inconel 625 and AISI 304 were obtained using GTA welding process by employing Mo rich filler wire such as ERNiCrMo-3. The weldments have been systematically characterized for their metallurgical and mechanical properties. The following chapters will give a detailed outline of the experimental methodology and the outcomes of the work.

2. Experimentation

The base metals employed in this study were 125 mm x 50 mm x 5 mm plates of Inconel 625 and AISI 304 and the filler metal ERNiCrMo-3. The nominal chemical composition of the base metals and the filler metal are represented in Table 1. The process parameters were established after conducting iterative studies by bead on plate welding on individual plates and are shown in Table 2. Standard V- groove butt joints with an included angle of 60° and a root face of 1 mm was employed for welding these bimetals. A specially designed fixture with a copper back plate that could clamp the base metals firmly was employed to avoid distortion and bending while welding. After welding, the weldments were characterized for NDT examination to determine for any flaws, porosities, undercut etc.

Table 1. Chemical Composition of the base metals and filler metal

Base / Filler Metal	Chemical Composition (% Weight)							
	C	Cr	Ni	Mn	Mo	Nb	Fe	Others
Inconel 625	0.059	21.05	62.1	0.235	8.23	3.3	Bal	0.024 (Co) ; 0.01(Cu); 0.004 (Al); 0.016 (Ti); 0.02 (V); 0.15 (W); 0.009 (P);0.014 (S); 0.434 (Si)
AISI 304	0.063	18.4	8.11	0.9	0.22	0.01	Bal	0.032 (P); 0.001 (S); 0.28 (Si)
ERNiCrMo-3	0.1	21.5	50	0.5	9.0	3.565	5.0	8.0 (Co); 0.5 (Cu); 0.4 (Al); 0.4 (Ti); 0.02 (P) ; 0.015 (S); 0.5 (Si)

Table 2. GTA welding parameters

Welding Type	Filler wire	Peak Current (Amps)	Voltage(V)	Shielding Gas Flow Rate (lpm)	Filler Wire Dia.(mm)	Heat Input (KJ/mm)
GTAW	ERNiCrMo-3	160-170	16-17	15.5	2.4	1.66

Followed by NDT analysis, the welded samples were cut using wire cut Electrical Discharge Machining (EDM) to different coupons of various dimensions to assess the metallurgical and mechanical properties. It is really cumbersome task to reveal the microstructure of the welded bimetallic joints due to the existence of different chemical compositions across the weldments.

The macro and microstructure studies were performed on the coupons termed as “composite region” which cover all the zones of the weldment. Composite region of the weldments was polished using

the emery sheets of SiC with various grit sizes from 220 to 1000 which was then followed by disc polishing using alumina solution so as to obtain a mirror finish of 1μ on the weldments. Electrolytic etching (10% oxalic acid solution; 6V DC supply and 1 A / Cm²) was employed to examine the microstructure of Inconel 625 whereas glyceragia was used for AISI 304 side. The weldments were cut to different coupons as per the standards to estimate the mechanical properties. Tensile studies were performed on the weldments which were made as per the ASTM E8 standards. Three trials on the weldments

were conducted to check the reproducibility of the results. The samples were tested at a strain rate of 2 mm/min at room temperature. Furthermore the fractured samples were characterized for SEM analysis to determine the mode of fracture. Hardness measurement was carried out on the composite region of the weldment using Vicker's Micro-hardness tester with a load of 500gf for a dwell time period of 10 s at regular intervals of 0.25 mm. Further the SEM/EDS analysis was performed on the various zones of the weldments to determine the presence of various elements and also helpful to assess the structure - property correlations. The following chapter addresses the results and discussions of the experimental work.

3. Results

3.1. Macro and Microstructure Examination

Visual examination, NDT analysis and the macrostructure examination [Fig. 1 (a) and (b)] clearly revealed that the dissimilar weldments obtained from GTA welding technique has been properly fused and not been observed with any macro/micro scale deficiencies. Microstructure of the dissimilar weldments clearly showed that the weld zone has been observed with dendritic growth. The grains observed at the HAZ of AISI 304 were found to be coarser [Fig. 2(b)]. Also the segregation or formation of secondary phases was formed at the HAZ of AISI 304.

3.2. Mechanical Characterization of the weldments

Hardness studies were carried out across the cross section of the GTA dissimilar weldments of Inconel 625 and AISI 304. From the hardness profile, it is evident that Inconel 625 side has maximum hardness [249.5 HV] as compared to the other zones of the weldments. The average hardness of the entire weldment was found to be 231.3 HV and the weld zone has the average hardness of 236.4 HV

Further tensile studies were conducted on the dissimilar weldments. During the transverse tensile tests, in all the trials, the GTA weldments failed at the parent metal of AISI 304 stainless steel. Significant plastic deformation had been observed before the fracture

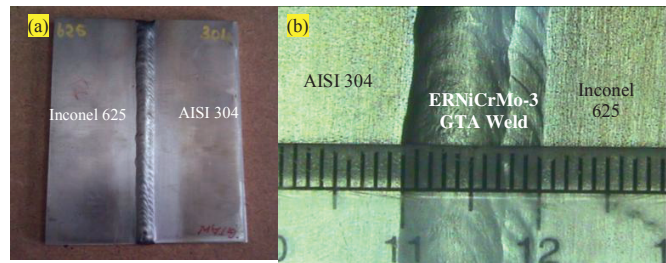


Fig. 1(a) Photograph of the GTA welded Inconel 625 and AISI 304 (b) Macrograph of the dissimilar joints

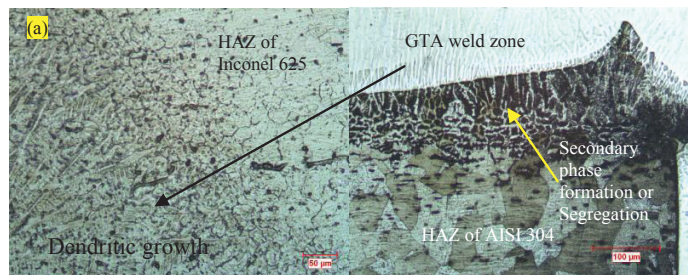


Fig. 2 Microstructure showing (a) Weld - HAZ of Inconel 625 (b) Weld - Weld Interface - HAZ of AISI 304

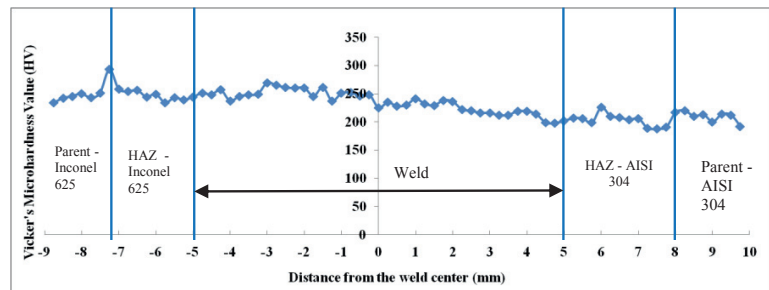


Fig.3 Hardness Profile of Inconel 625 and AISI 304 GTA weldments

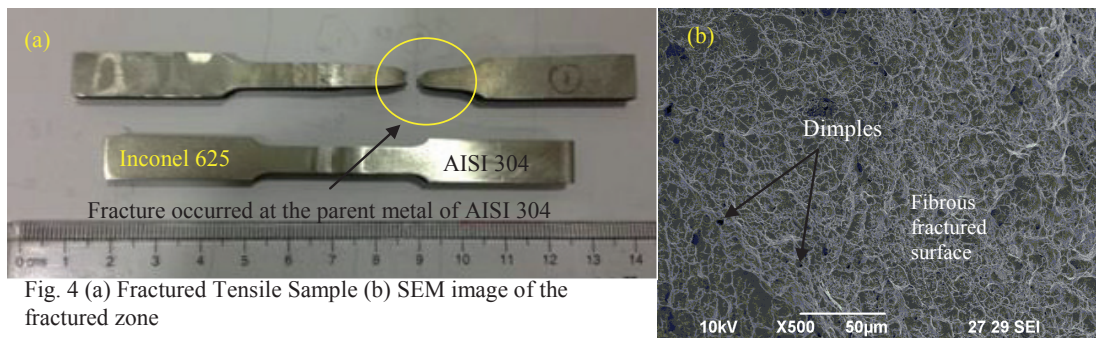


Fig. 4 (a) Fractured Tensile Sample (b) SEM image of the fractured zone

occurs. The average tensile test properties of the GTA weldments are represented in Table 3. The ductility measured in terms of percentage elongation at the break load was found to have an average 55.11 % for GTA weldments and the average ultimate tensile strength of these dissimilar combinations was found to be as 726 for GTA and PCGTA weldments respectively. Fig. 4 (b) represents the SEM fractographs of the tensile failure samples. SEM fractographs confirmed the formation of micro-voids and small dimples dispersed at the fibrous network which tend to coalesce together to undergo ductile fracture.

Table 3. Average Tensile Properties of Inconel 625 and AISI 304 GTA and PCGTA weldments

Welding	UTS (MPa)	Young's Modulus (GPa)	% Elongation at Break Load	Fracture Zone
GTA	726	62.2	55.11	Parent Metal of AISI 304

3.3. SEM/EDAX analysis on the weldments

SEM/EDAX analysis on the composite region of the GTA weldments is shown in Fig. 5. It is evident from the analysis that the HAZ of AISI 304 has richer amounts of Fe, Ni, Cr and Mo and the elements such as Mn, Nb and Si was found to be in lesser amounts. Whereas the weld zone and the HAZ of Inconel 625 have been enriched with Ni, Cr, Mo and Nb and the presence of the elements such as Fe, Al, and Ti were also being noticed. The EDAX results are represented in Table 4.

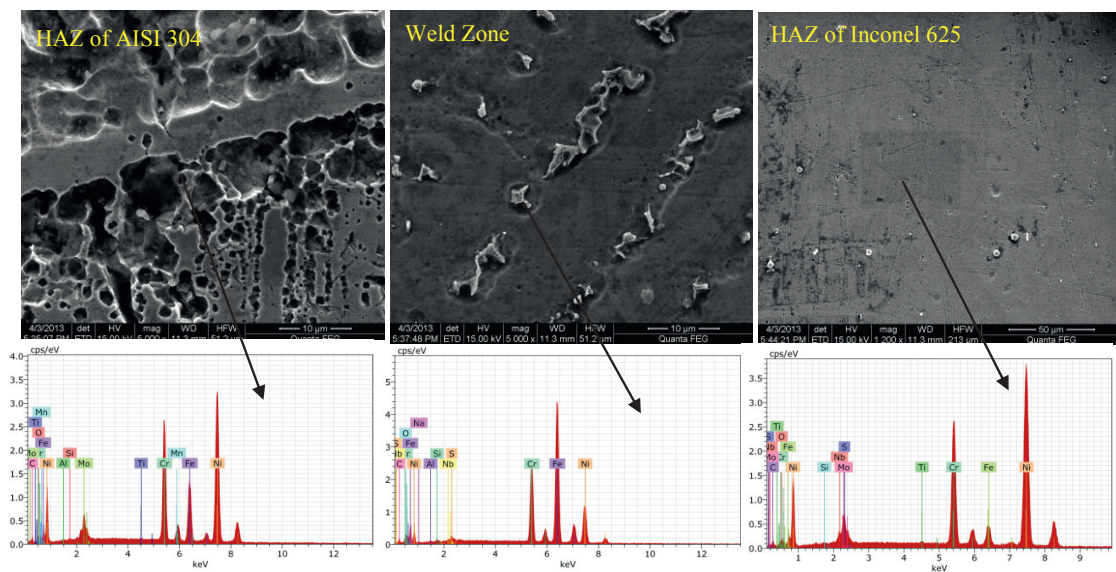


Fig. 5 SEM/EDAX analysis on the composite region of the weldment in the as-welded conditions

Table 4. EDAX analysis (wt %) on Inconel 625 and AISI 304 GTA weldments

Element Zone	Fe	Cr	Ni	C	Si	P	S	Ti	Mn	Al	Mo	Nb
HAZ of AISI 304	47.43	15.98	20.31	8.88	0.11	0.49	0.79	-	0.42	0.47	4.03	0.77
Weld Zone	13.72	19.18	51.82	7.45	0.18	-	-	0.12	0.11	0.16	6.11	3.25
HAZ of Inconel 625	4.14	18.51	57.6	7.79	0.09	0.25	0.21	0.28	0.24	0.11	6.58	4.16

4. Discussions

The absence no micro/macro-scale deficiencies in the GTA weldments as accentuated from the NDT analysis clearly recommended that GTA welding could be employed for joining Inconel 625 and AISI 304 using ERNiCrMo-3. It is also evident that the process parameters employed for welding these dissimilar metals were also found to be optimal. As

envisaged from the microstructure studies, the weld zone has the dendritic structure and the HAZ of AISI 304 has been witnessed with segregation effects. As reported by other researchers, the weld zone is fully austenitic. During solidification, Nb would be easily redistributed in to inter-dendritic regions and produces Nb enriched carbides [1]. However higher amounts of nickel and lower amounts of chromium in this weld metal can dissolve an increased amount of niobium in austenite and reduce segregation of Nb along the boundaries as well [5]. As reported by Farahani et al.[8], CCGTA welding could result in the segregation at the weld interface of AISI 304 side and moreover the amounts of Ni and Cr is not sufficient to dissolve Nb that could resulted in the formation of secondary phases [9]. It was also observed that solidification cracking tendency was totally avoided in the weld zone on using ERNiCrMo-3 filler wire. As reported by Shah Hosseini et al. [1], on using lower heat input during welding could result in a higher cooling rate and consequently a finer microstructure. This fine microstructure had a lower segregation ratio of Mo which makes the welds brittle at room temperature. Therefore, the solidification cracking tendency was reduced. This is in agreement with the work and envisaged from the SEM/EDAX analysis.

It is evident from the hardness tests that the weld region and weld interfaces have acquired the maximum hardness which is due to the presence of higher amounts of Nb, Ni, Cr and C. As evident from the This could be due to the formation of significant amounts of NbC, (Nb,Ti)C and Cr₂₃C₆. Jeng et al. [7] observed the tensile fracture at the fusion zone for Alloy 690 and SUS 304L SMA weldments. The authors further witnessed that non-homogeneous distribution of Nb had occurred at the fusion zone due to the welding techniques employed in this study. It is observed clearly that the filler wire and the process parameters employed in this study were optimal and also clearly indicate that the weld strength would be higher than the strength of the candidate metals.

Conclusions

The typical filler metal ERNiCrMo-3 was used to obtain dissimilar Inconel 625/304 austenitic stainless joint using the gas tungsten arc welding process. The following conclusions can be drawn from the results:

1. Successful weldments of Inconel 625 and AISI 304 could be obtained by the GTA welding process employing ERNiCrMo-3
2. The weld microstructure was fully austenitic; Segregation effects have been witnessed at the interface of AISI 304
3. Hot cracking tendency was totally avoided on using Mo rich filler wire and the lower heat input employed in the GTA welding
4. In all the trials of tension tests, the GTA weldments undergo ductile fracture with considerable amounts of plastic deformation

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